Using ND Measurements to Improve Expected FD Event Rate

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Outline

Basic Idea

- Recognize that neutrinos in the ND and FD come from the same hadron decays.
- Correlate ND and FD event spectra
- Apply correlation to measured ND spectrum
- In principle, reduces beam related uncertainties (hadron production, target/horn geometries)

Method as I understand it

1) For each GNUMI neutrino, fill the 2D histogram bin holding E_ν^f, E_ν^n weighted by:

$$M_{E_\nu^n, E_\nu^f} = \int_{E_\nu^n}^{E_\nu^n+\Delta E_\nu} dE_\nu^{FD} \int_{E_\nu^f}^{E_\nu^f+\Delta E_\nu} dE_\nu^{ND} \frac{W_h^{FD}(\vec{r}, \vec{p}, E_\nu^{FD})\sigma_{\mathrm{CC}}(E_\nu^{FD})}{W_h^{ND}(\vec{r}, \vec{p}, E_\nu^{ND})\sigma_{\mathrm{CC}}(E_\nu^{ND})} \tag{1}$$

- h Hadron (π or k)
- $\vec{r}, \vec{p}$ hadron decay parameters
- W probability for decay to produce neutrino at ND/FD detector with

The NuMI note states that one should form a ratio of integrals, not an integral of ratios. I think this is just a LaTeX-o.

Method as I understand it, continued

2) Measure reconstructed ν_μ CC "like" energy spectrum in the ND, binned to match the 2D matrix just formed: $N^{ND,exp}_{E_{reco}}$
3) Multiply to get expected FD E_{reco} spectrum.

$$N^{FD,exp}_{E_{reco}} = M_{E^n_\nu,E^f_\nu} N^{ND,exp}_{E_{reco}} \tag{2}$$

Perceived Problems with this Method

- Ad-hoc, or at best, not fully described/understood.
- Applies E_ν matrix to E_{reco} vector.
- Ignores:
  - Detector response
  - Reconstructed energy resolution
- ν_μ CC (or at least single-interaction) specific. Want to apply to beam-related ν_e background which has multiple sources.

Now, try to get this....

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What GNUMI does

From NuMI-B-781, neutrino energy distribution at i^{th} detector due to hadron type h.

$$\Phi_i(E_\nu) = \int F_h(\vec{h_0}, \vec{p}) P_h(\vec{h_0}, \vec{p}, \vec{r}) W_h(\vec{h_0}, \vec{p}, \vec{r}; E_\nu) dh_0 d\vec{p} d\vec{r} \tag{3}$$

Parameters:

- $\vec{h_0}$ Initial hadron location and direction just after last horn.
- $\vec{p}, \vec{r}$ Hadron momentum, location at decay point

Functions:

- F_h Hadron distribution just after last horn
- P_h Probability initial hadron will decay at $\vec{r}$ and $\vec{p}$
- W_h Probability this hadron will produce ν with E_ν at i^{th} detector.

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Matricize

Integrate over nuisance $\vec{h_0}$ and small bins of E_ν and $\vec{h} = (\vec{p}, \vec{r})$ to give a matrix form:

$$\vec{\Phi}_{i,E_\nu} = T_{hi}\vec{H} \tag{4}$$

Where,

$\vec{H}$ is a multi-rank vector holding the binned distribution of parent hadrons over the space $\vec{h}$

T_{hi} is a transfer matrix that takes $\vec{H}$ to:

$\vec{\Phi}_{i,E_\nu}$ is the binned ν flux spectrum at the i^{th} detector.

Note:

- $\vec{H}$ is independent from what detector. This is the correlation we want to exploit.
- T_{hi} is simply analytical.
- There is actually one such equation per parent hadron and neutrino type.

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What Everything Else Does

Model Interaction + Detector + Reconstruction + Cuts as

$$M^{\nu,\sigma,c,i,s}_{E_{reco},E_\nu} \tag{5}$$

In general one M for each:

- ν neutrino type
- σ interaction type
- c Reconstruction classification (signal or background)
- i Detector (near or far)
- s Data source (real data, simulated MC)

Binned event spectrum at the i^{th} detector:

$$\vec{N}^{i,s,c}_{E_{reco}} = \sum_{\nu,\sigma} M^{\nu,\sigma,c,i,s}_{E_{reco},E_\nu} \vec{\Phi}_{i,E_\nu} \tag{6}$$

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The Formal Method

(For simplicity, consider one ν, σ and c.)

1. Predict ND reconstructed neutrino energy spectrum:

$$\vec{N}^{n,MC}_{E_{reco}} = M^{n,MC}_{E_{reco},E_\nu} \vec{\Phi}_{n,E_\nu} \tag{7}$$

2. Assert $\vec{N}^{n,data}_{E_{reco}} \equiv \vec{N}^{n,MC}_{E_{reco}}$ and claim to measure flux at ND and recall flux comes from decaying hadrons:

$$\vec{\Phi}^{meas}_{n,E_\nu} = \left(M^{n,MC}_{E_{reco},E_\nu}\right)^{-1} \vec{N}^{n,data}_{E_{reco}} = T_{hn}\vec{H} \tag{8}$$

3. Solve for $\vec{H}$ (exploit the corelation!) and claim to measure far flux

$$\vec{\Phi}^{meas}_{f,E_\nu} = T_{hf}\, T^{-1}_{hn} \left(M^{n,MC}_{E_{reco},E_\nu}\right)^{-1} \vec{N}^{n,data}_{E_{reco}} \tag{9}$$

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Some Obvious Caveats

- Asserting $\vec{N}^{n,data}_{E_{reco}} \equiv \vec{N}^{n,MC}_{E_{reco}}$ to measure the ND flux trusts that our MC is good and our reco is same between MC and data! How to estimate systematics here?
- Need to have a $\vec{\Phi}^{meas}_{f,E_\nu}$ for each parent hadron type, neutrino type.
- Still need to get to $\vec{N}^{f,meas}_{E_{reco}}$. Probably just re-weight reconstructed MC events via $\vec{\Phi}^{meas}_{f,E_\nu} / \vec{\Phi}^{MC}_{f,E_\nu}$.

How to actually do this?

$$\vec{\Phi}^{meas}_{f,E_\nu} = T_{hf}\, T^{-1}_{hn} \left(M^{n,MC}_{E_{reco},E_\nu} \right)^{-1} \vec{N}^{n,data}_{E_{reco}} \tag{10}$$

T_{hf} : The transport matrix is exactly calculable. It is only a little ungainly being such a high rank matrix.

T^{-1}_{hn} : Ditto. Inverting might prove tricky?

$\left(M^{n,MC}_{E_{reco},E_\nu} \right)^{-1}$: Simple, fill a 2D histogram with reconstructed ND GMINOS events.

$\vec{N}^{n,data}_{E_{reco}}$ Even easier, fill 1D histogram from reconstructed ND data.